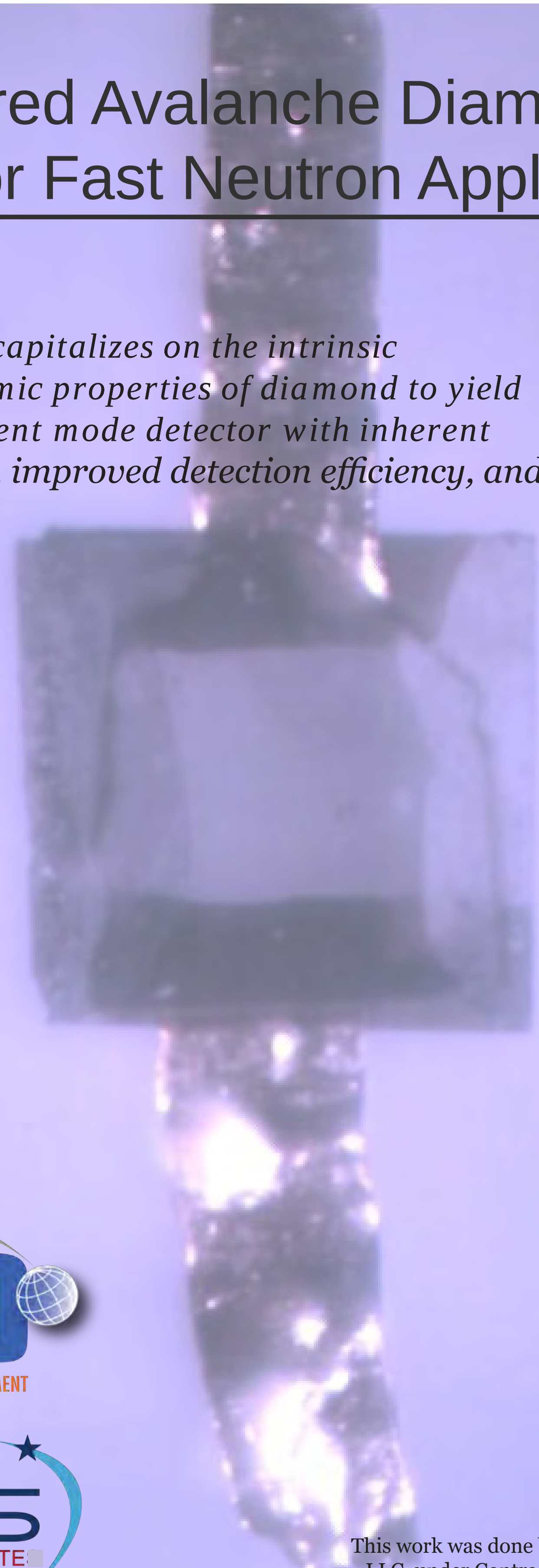
# Multi-Layered Avalanche Diamond Detector for Fast Neutron Applications

**R&D 100 Entry 2023**

*The MAD detector capitalizes on the intrinsic avalanche and atomic properties of diamond to yield a fast neutron current mode detector with inherent multiplicative gain, improved detection efficiency, and a small footprint.*



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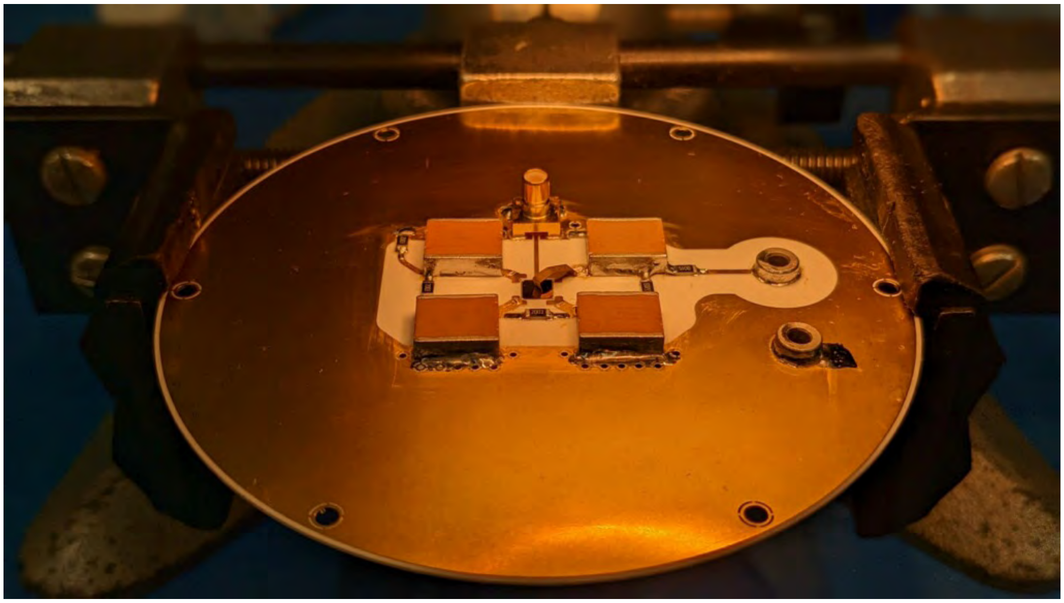
# Summary

The Multilayered Avalanche Diamond (MAD) detector provides a solid-state solution to detecting neutrons with more than six times the inherent multiplicative gain possible with commercially available single-layer bulk diamond detectors. The MAD detector provides low noise, high fidelity current mode measurements of neutron sources. It also has the high gamma ray rejection and intrinsic detection efficiency required across the Department of Energy Scientific Laboratory Complex. In addition, it also enables neutron time-of-flight (TOF) measurements and contributes to spectroscopic capabilities otherwise not available. The MAD detector enables all of this in a compact package, enabling these measurements in very tight spaces.



*The Multi-Layered Avalanche Diamond (MAD) detector.*

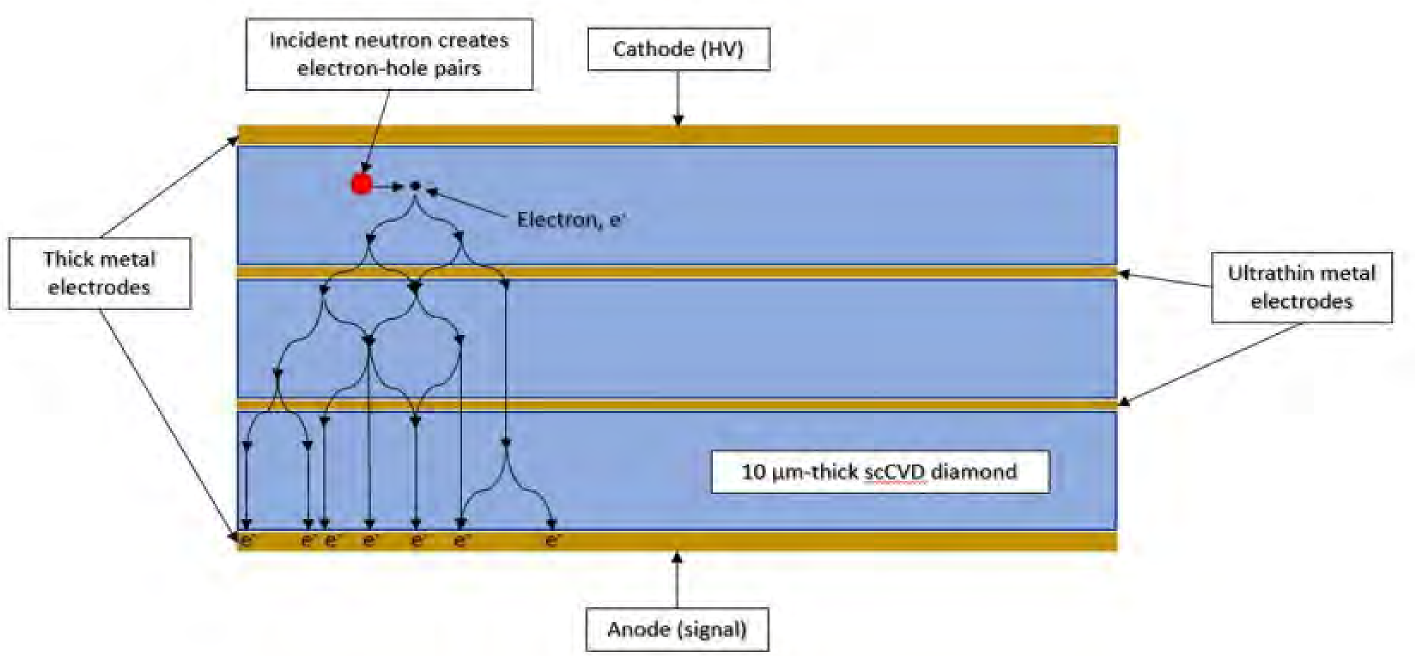
# Product Description

*What Does the Product Do?*

Diamond photoconductive detectors detect fast neutrons with high gamma insensitivity. Applying a large electric field (30 100 V/μm) across a thin single crystal chemical vapor deposition (scCVD) diamond induces the avalanche effect within that diamond layer. The MAD detector uses three 10 μm thick scCVD diamond layers with ultrathin metal electrodes between each diamond layer. Electrons born from incident radiation traverse the ultrathin metal layers and go on to create secondary electron-hole pairs in subsequent diamond layers. Thus, charge multiplication across diamond layers is achieved.

The primary application of the MAD detector is to provide an inherently high gain and low noise current mode measurement of a pulsed neutron source (typically in beam lines, synchrotrons, colliders, and cyclotrons). The MAD Detector can be used at the National Ignition Facility (NIF), Sandia National Laboratories' Z machine, and for the Nevada National Security Site's (NNSS) Neutron Diagnosed Subcritical Experiments (NDSE) and High Energy Density Science (HEDS). These detectors will also find use as neutron time-of-flight (TOF) spectrometers in support of the NNSS Stockpile Stewardship Program and Global Security Mission. The NDSE project leadership and scientists at both the NNSS and Los Alamos National Laboratory have selected the MAD detector to be fielded on an NDSE static series campaign in late 2023.

The MAD detector could also be used in satellite and stellar instrumentation, and with intensity modulated radiation therapy and medical dosimeters. Another application possibility is nuclear power and re-processing plants.




*MAD detector vertical compression-bonded stack, 30 μm × 4 mm × 4 mm. Cutaway reveals several 10 μm thick internal diamond multilayers with ultrathin metallization (gold).*

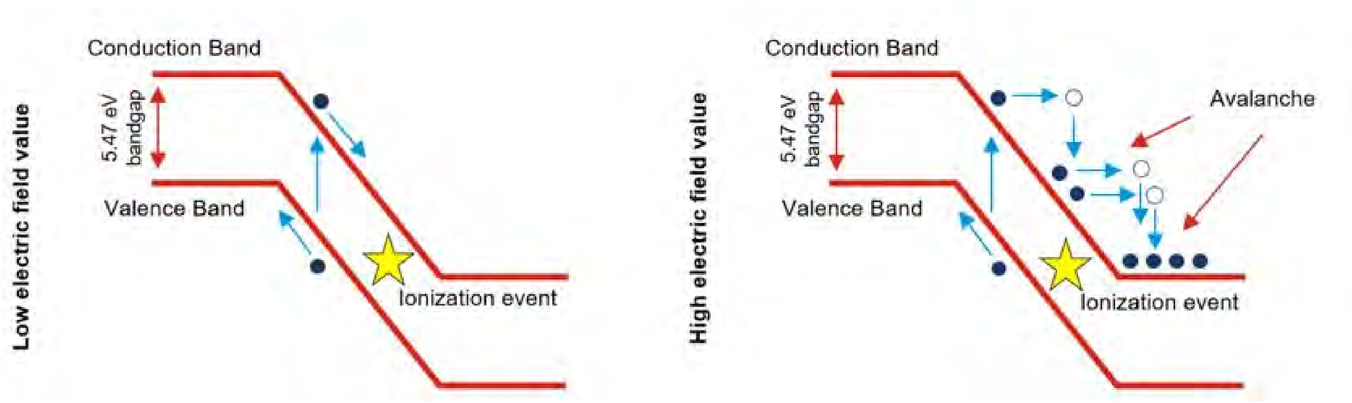
# Product Description (cont.)

*How Does the Product Operate?*

The multilayered avalanche diamond (MAD) detector stacks individual electronic grade single crystal chemical vapor deposition (scCVD) diamonds on top of one another with interweaving ultrathin metal electrodes mounted to a tailored printed circuit board (PCB). Thin diamonds (i.e., a few micrometers thick) are used and a high bias voltage (30 volts/µm or greater) is applied to the device. This multi-layer configuration enables charge multiplication in the individual layers and multiplicative gain across several layers when a neutron, or other radiation quanta, interacts in the detector.

The MAD detector maintains geometrical gain similar to the way a photomultiplier tube (PMT) does, providing an increased signal-to-noise ratio and flexibility in fielding the detector further from the source. The gain in signal with the MAD detector is made possible by the avalanche effect. The avalanche effect is electron-hole multiplication achieved by increasing the electric field within the scCVD diamond high enough such that secondary electrons created from radiation interactions in the diamond can be kinetically accelerated beyond the band gap energy before colliding or scattering within the lattice. Electrons at avalanche speeds have enough energy to transit a thin metal layer (~10 nm) and can be transported between vertically stacked layers to continue producing compounded secondaries resulting in multiplicative gain. The proximity of the metal layers in a thin diamond layer are key to a sustained field in the presence of significant charge generation.

Significantly higher gain was observed with the MAD detector in comparison to a single 10 µm-thick scCVD diamond detector. Measurements with the MAD detector under a displacement field (bias voltage divided by device thickness) of 29.3 V/µm yielded a gain of 6.39 x or 16.2 dB.




*Depiction of electron-hole multiplication and thus, the avalanche effect that is employed in the MAD detector.*

Measurements with a single 10 µm-thick scCVD diamond detector under the same displacement field yielded a gain of 1.52 x or 3.64 dB. If the Mad detector gain were merely additive, we would expect a gain of 4.56 x or 13.2 dB, not 6.39 x or 16.2 dB.

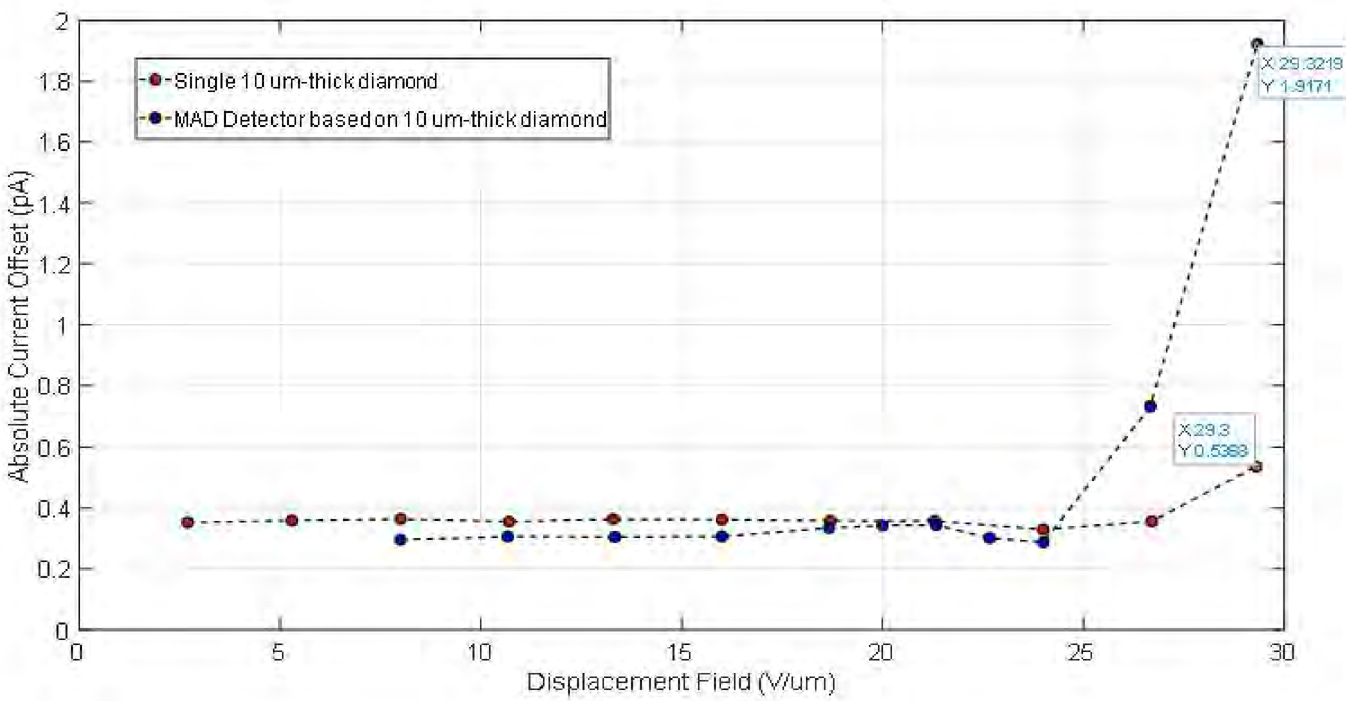
This result indicates that charge multiplication is not only occurring within each diamond layer but also by electrons traversing the ultrathin metal electrode between diamond layers, creating further avalanche events in subsequent diamond layers.

In addition to the multiplicative gain, employing scCVD diamond in the MAD detector boasts other attractive properties for current mode detection of neutrons. scCVD exhibits high radiation hardness, a wide (5.5 eV) band gap, a full-width half-maximum on the order of 1 ns, and superior long-term stability. The high atomic density and low atomic number of diamonds translates into a high neutron detection efficiency per unit volume and limits gamma ray interaction. ◆

# How Does This Improve upon Competitive Products?

The typical commercially available scCVD diamond detector has one 500 µm-thick diamond layer and two thick electrical contacts on either side. This device has no inherent gain without applying an unreasonably high bias voltage (i.e., 15 kV) to it. Furthermore, it must be fielded very close to the neutron source or with an external amplifier to obtain a measurable signal. The limitation on how close the detector needs to be to obtain a measurable signal takes up premium space within the environment. External amplifiers introduce unwanted noise and take up space that can already be limited. The close proximity also eliminates the possibility of performing other types of neutron measurements such as neutron time-of-flight (nToF), which requires meters of distance between the detector and the neutron source.

The inherent multiplicative gain of the MAD detector yields a signal-to-noise ratio high enough such that no external amplification is needed, and it allows the detector to be useful in a variety of scenarios less proximate to the source.




*Offset current versus displacement field for MAD detector compared to a single 10 µm-thick diamond detector.*

# Limitations of the Product

Electric field values up to 1,000 V/um are theoretically achievable with scCVD diamond. However, application of electric field values greater than 30 V/um have not been investigated extensively with the MAD detector. The dark current observed in the MAD detector at electric field values greater than 30 V/um appears to swamp the signal of interest. Future generations of the MAD detector aim to address this because the higher the electric field value that can be applied, the higher the gain that can be achieved while holding constant the number of diamond layers and the diamond layer thickness.